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14. ABSTRACT
Arid and semiarid landscapes in regions with seasonal precipitation experience dramatic changes that alter land surface conditions, including soil moisture states, ecosystem productivity and river flooding. These variations in terrestrial properties have implications for vehicle mobility, airborne surveillance, target acquisition and aircraft operations and for battlefield environmental predictions supporting these operations. In this research, we developed and demonstrated novel approaches for terrestrial science studies by integrating the deployment of environmental

15. SUBJECT TERMS
ecohydrology, unmanned aerial vehicles, environmental sensor networks, distributed hydrologic modeling, vegetation dynamics, soil moisture, evapotranspiration, remote sensing, North American monsoon

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Report Title

Final Report: Effects of Seasonal Land Surface Conditions on Hydrometeorological Dynamics in South-western North America

ABSTRACT

Arid and semiarid landscapes in regions with seasonal precipitation experience dramatic changes that alter land surface conditions, including soil moisture states, ecosystem productivity and river flooding. These variations in terrestrial properties have implications for vehicle mobility, airborne surveillance, target acquisition and aircraft operations and for battlefield environmental predictions supporting these operations. In this research, we developed and demonstrated novel approaches for terrestrial science studies by integrating the deployment of environmental sensor networks, unmanned aerial vehicle data acquisition and high performance computing-based hydrologic modeling designed to capture, account for and predict seasonal variations in land surface conditions. Our tests are focused in a range of arid and semiarid sites in southwestern North America that are representative of operational environments undergoing strong seasonality.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/16/2010	1.00	E. Vivoni, J. Rodriguez, C. Watts. On the spatiotemporal variability of soil moisture and evapotranspiration in a mountainous basin within the North American monsoon region, Water Resources Research, (02 2010): . doi:
08/23/2013	5.00	Enrique Vivoni. Diagnosing Seasonal Vegetation Impacts on Evapotranspiration and Its Partitioning at the Catchment Scale during SMEX04–NAME, Journal of Hydrometeorology, (10 2012): 1631. doi:
08/29/2012	3.00	Enrique R. Vivoni. Spatial patterns, processes and predictions in ecohydrology: integrating technologies to meet the challenge, EcoHydrology, (05 2012): 235. doi: 10.1002/eco.1248
08/30/2014	8.00	Ryan C. Templeton, Enrique R. Vivoni, Luis A. Méndez-Barroso, Nicole A. Pierini, Cody A. Anderson, Albert Rango, Andrea S. Laliberte, Russell L. Scott. High-resolution characterization of a semiarid watershed: Implications on evapotranspiration estimates, Journal of Hydrology, (02 2014): 0. doi: 10.1016/j.jhydrol.2013.11.047
08/30/2014	9.00	Luis A. Méndez-Barroso, Enrique R. Vivoni, Agustin Robles-Morua, Giuseppe Mascaro, Enrico A. Yépez, Julio C. Rodríguez, Christopher J. Watts, Jaime Garatuza-Payán, Juan A. Saíz-Hernández. A modeling approach reveals differences in evapotranspiration and its partitioning in two semiarid ecosystems in Northwest Mexico, Water Resources Research, (04 2014): 0. doi: 10.1002/2013WR014838
09/10/2015	16.00	Enrique Vivoni, Al Rango, Cody Anderson, Nicole Pierini, Adam Schreiner-McGraw, Srikanth Saripalli, Andrea Laliberte. Ecohydrology with unmanned aerial vehicles, Ecosphere, (10 2014): 130. doi:
09/10/2015	17.00	Nicole Pierini, Enrique Vivoni, Agustin Robles-Morua, Russell Scott, Mark Nearing. Using observations and a distributed hydrologic model to explore runoff thresholds linked with mesquite encroachment in the Sonoran Desert, Water Resources Research, (10 2014): 8191. doi:
09/10/2015	18.00	Dawn Browning, Al Rango, Jason Karl, Christine Laney, Enrique Vivoni, Craig Tweedie. Emerging technological and cultural shiftsadvancing drylands research and management, Frontiers in Ecology and the Environment, (01 2015): 52. doi:
09/10/2015	19.00	Giuseppe Mascaro, Enrique Vivoni, Luis Mendez-Barroso. Hyperresolution hydrologic modeling in a regional watershed and its interpretation using empirical orthogonal functions, Advances in Water Resources, (06 2015): 190. doi:

TOTAL: 9

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Vivoni, E.R. 2009. Observations and modeling of the effects of seasonal vegetation cover on evapotranspiration and soil moisture. ARO Meeting at the Topographic Engineering Center, Alexandria, VA.

2. Vivoni, E.R. 2009. Signatures of Seasonal Vegetation Dynamics on Catchment Hydrology in the North American Monsoon Region. AGU Fall Conference. San Francisco, CA.

3. Vivoni, E.R. 2010. Seasonality of Watershed Hydrology Induced by Remotely-sensed Vegetation Dynamics. U.S. Army Environmental Sciences Coordinating Group Meeting. Hanover, NH.

4. Vivoni, E.R. 2010. Land Surface Ecohydrology of the North American Monsoon System, Research Insights in Semiarid Ecosystems, 10th Symposium, Tucson, AZ.

5. Vivoni, E.R. 2010. Impacts of Vegetation Dynamics on Watershed Hydrology. Army Research Office Meeting, Vicksburg, MS.

6. Templeton, R.C., Vivoni, E.R., Mendez-Barroso, L.A., Rango, A., Laliberte, A.S. and Saripalli, S. 2010. Emerging Technologies for Ecohydrological Studies during the North American Monsoon in a Chihuahuan Desert Watershed. American Geophysical Union Fall Meeting, San Francisco, CA.

7. Mendez-Barroso, L.A., Vivoni, E.R., Rodriguez, J.C., Watts, C.J., Garatuza-Payan, J. and Yepez, E.A. 2010. Seasonal Evolution, Interannual Variability and Partitioning of Evapotranspiration in Two Mountainous Semiarid Forest Ecosystems. American Geophysical Union Fall Meeting, San Francisco, CA.

8. Vivoni, E.R. and Mendez-Barroso, L.A. 2011. Spatiotemporal Variations in Evapotranspiration Partitioning with the North American Monsoon Region: Role of Vegetation Dynamics. 91st Annual American Meteorological Society Meeting, Seattle, WA.

9. Templeton, R.C., Vivoni, E.R., Mendez-Barroso, L., Laliberte, A. and Rango, A. 2011. Redesigning the Small Catchment Study: Distributed Model Evaluation in a Chihuahuan Desert basin and the Impact of Model Coarsening. 24th Annual Symposium, Arizona Hydrological Society, Flagstaff, AZ.

10. Pierini, N.A., Templeton, R.C., Robles-Morua, A., and Vivoni, E.R. 2011. Sonoran Desert Vegetation Shifts and Watershed-Scale Ecohydrological Dynamics during the North-American Monsoon. American Geophysical Union Fall Meeting, San Francisco, CA.

11. Rango, A. and Vivoni, E.R. 2012. Hydrology with Unmanned Aerial Vehicles (UAVs). AGU Chapman Conference on Remote Sensing of the Terrestrial Water Cycle. Kona, Hawaii.

12. Pierini, N.A., Templeton, R.C., Robles-Morua, A. and Vivoni, E.R. 2011. Watershed-scale ecohydrological dynamics in the Santa Rita Experimental Range. Research Insights in Semiarid Ecosystems (RISE). Tucson, AZ.

13. Anderson, C.A., Vivoni, E.R., Pierini, N., Templeton, R.C., Rango, A., Laliberte, A. and Saripalli, S. 2012. Characterization of shrubland-atmosphere interactions through use of the eddy covariance method and distributed footprint sampling. 17th Wildland Shrub Symposium. Las Cruces, NM.

14. Vivoni, E.R., Templeton, R.C., Méndez-Barroso, L.A., Rango, A. and Laliberte, A.S. 2012. Advances in Watershed Characterization using Sensor Networks and Unmanned Aerial Vehicle Products in a Mixed Shrubland. 17th Wildland Shrub Symposium. Las Cruces, NM.

15. Rango, A. and Vivoni, E.R. 2012. Hydrology with Unmanned Aerial Vehicles (UAVs). Jornada Centennial Symposium. Las Cruces, NM.

16. Rango, A., Vivoni, E.R., Anderson, C.A., Pierini, N.A., Saripalli, S. and Laliberte, A. 2012. Application of high resolution images from unmanned aerial vehicles for hydrology and rangeland science. American Geophysical Union Fall Meeting, San Francisco, CA.

17. Pierini, N.P., Vivoni, E.R., Anderson, C.A., Saripalli, S. and Robles-Morua, A. 2012. Distributed Modeling Reveals the Ecohydrological Dynamics Linked with Woody Plant Encroachment in the Sonoran Desert. American Geophysical Union Fall Meeting, San Francisco, CA.

18. Anderson, C.A., Vivoni, E.R., Pierini, N., Robles-Morua, A., Rango, A., Laliberte, A. and Saripalli, S. 2012. Characterization of Shrubland-Atmosphere Interactions through Use of the Eddy Covariance Method, Distributed Footprint Sampling and Imagery from Unmanned Aerial Vehicles. American Geophysical Union Fall Meeting, San Francisco, CA.

19. Vivoni, E.R., Pierini, N.A., Anderson, C.A., Schreiner-McGraw, A., Robles-Morua, A., Mendez-Barroso, L.A. and Templeton, R.C. 2013. Watershed-Scale Ecohydrological Studies of Woody Plant Encroachment in Sonoran and Chihuahuan Desert Landscapes. AGU Meeting of the Americas, Cancun, Mexico.

20. Anderson, C.A., Vivoni, E.R., and Rango, A. 2013. Characterization of Shrubland-Atmosphere Interactions Through Use of the Eddy Covariance Method, Distributed Footprint Sampling and Imagery from UAVs. AZ Water Association Conference, Phoenix, AZ.

21. Schreiner-McGraw, A., Vivoni, E.R., Franz, T., and Anderson, C.A. 2013. Application of Cosmic-ray Soil Moisture Sensing to Understand Land-atmosphere Interactions in Three North American Monsoon Ecosystems. AGU Fall Meeting, San Francisco, CA.

22. Rango, A., Browning, D.M., Vivoni, E.R., Anderson, C.A., and Laliberte, A.S. 2013. Utilization of Unmanned Aerial Vehicles for Rangeland Resources Monitoring in a Changing Regulatory Environment. AGU Fall Meeting, San Francisco, CA.

23. Vivoni, E.R. 2014. Las Interacciones Atmósfera-Tierra Durante el Monzón de América del Norte: Estudios Ecohidrológicos de Modelación y de Campo. Reunión Anual Union Geofísica Mexicana. Puerto Vallarta, Jalisco, Mexico.

24. Schreiner-McGraw, A. and Vivoni, E.R. 2015. Application of Cosmic-ray Soil Moisture Sensing to Understand Land-atmosphere Interactions in three North American Monsoon Ecosystems. American Meteorological Society Annual Meeting, Phoenix, AZ.

25. Pierini, N.P., and Vivoni, E.R. 2015. A Distributed Hydrologic Model Application to Explore Ecohydrological Dynamics of Mesquite Encroachment during Winter and Summer Conditions. American Meteorological Society Annual Meeting, Phoenix, AZ.

26. Schreiner-McGraw, A., Vivoni, E.R., and Browning. D.M. 2015. Shrub Strategies in a Competition for Water Determine Ecosystem State. Ecological Society of America, Baltimore, MD.

27. Mascaro, G., Mendez-Barroso, L.A., and Vivoni, E.R. 2015. Quantifying the Hydrologic Response of a Regional Basin in Northwest Mexico through High-Resolution Hydrologic Simulations. American Meteorological Society Annual Meeting, Phoenix, AZ.

Number of Presentations: 27.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/23/2013	6.00	Ryan Templeton, Enrique Vivoni, Luis Mendez-Barroso, Nicole Pierini, Cody Anderson, Albert Rango, Andrea Laliberte, Russell Scott. High-Resolution Characterization of a Semiarid Watershed: Implications onEvapotranspiration Estimates, Journal of Hydrology (04 2013)
08/29/2012	2.00	Enrique Vivoni. Diagnosing Seasonal Vegetation Impacts on Evapotranspiration and Its Partitioningat the Catchment Scale during SMEX04–NAME, Journal of Hydrometeorology (06 2012)
08/30/2014	12.00	Albert Rango, Enrique R. Vivoni, Cody A. Anderson, Nicole A. Pierini, Adam P. Schreiner-McGraw, Srikanth Saripalli, Andrea S. Laliberte. Ecohydrology with Unmanned Aerial Vehicles, Ecosphere (06 2014)
08/30/2014	13.00	Nicole A. Pierini, Enrique R. Vivoni, Agustin Robles-Morua, Russell L. Scott, Mark A. Nearing. Using Observations and a Distributed Hydrologic Model to Explore RunoffThresholds Linked with Mesquite Encroachment in the Sonoran Desert, Water Resources Research (04 2014)
09/09/2015	14.00	Cody Anderson, Enrique Vivoni. Land Surface States within the Flux Footprint Impact Land-Atmosphere Coupling in Two Semiarid Ecosystems of the Southwestern U.S., Water Resources Research (08 2015)
09/10/2015	15.00	Adam Schreiner-McGraw, Enrique R. Vivoni, Giuseppe Mascaro, Trenton E. Franz. Closing the Water Balance with Cosmic-ray Soil Moisture Measurements and Assessing Their Spatial Variability within Two Semiarid Watersheds, Hydrology and Earth System Sciences (05 2015)

TOTAL: **6**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

US Fulbright Scholar, 2015-2016.
US Frontiers of Engineering Participant, National Academy of Engineering, 2015.
Visiting Sabbatical Researcher, Mexican Council of Science and Technology, 2015-2016.
Distinguished Visiting Professor, Mexican Academy of Sciences, 2015.
Leopold Leadership Fellow, Woods Institute for the Environment, Stanford University, 2015-2016.
Walter L. Huber Civil Engineering Research Prize, American Society of Civil Engineering, 2014.
White House, Presidential Early Career Award for Scientists and Engineers (PECASE), 2009-2014.
Kavli Fellow, Kavli Frontiers of Science Participant, National Academy of Sciences, 2010.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Ryan Templeton	1.00	
Nicole Pierini	0.75	
Cody Anderson	1.00	
Adam Schreiner-McGraw	0.75	
Luis Mendez-Barroso	0.50	
FTE Equivalent:	**4.00**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Enrique Vivoni	0.10	
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME	
Ryan Templeton	
Nicole Pierini	
Cody Anderson	
Total Number:	**3**

Names of personnel receiving PHDs

NAME	
Luis Mendez-Barroso	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment.

Technology Transfer

None.

Effects of Seasonal Land Surface Conditions on Hydrometeorological Dynamics in Southwestern North America

ARO Tracking Number 53305-EV-PCS

Enrique R. Vivoni, Nicole A. Pierini, Adam Schreiner-McGraw, Cody A. Anderson,
Ryan C. Templeton and Luis A. Mendez-Barroso
School of Earth and Space Exploration
School of Sustainable Engineering and the Built Environment
Arizona State University

The Earth's land surface experiences seasonal changes that affect its physical, chemical and biological properties. In arid and semiarid regions, seasonal variations of water availability can dramatically impact land surface conditions (vegetation, soil moisture, surface temperature, heat fluxes) that potentially alter vehicle mobility, airborne surveillance, target acquisition and aircraft operations. Our study focused on gathering observational data sets in two major deserts of North America that will permit quantifying the seasonal transitions in land surface characteristics and enable the development of model applications that take these seasonal effects into consideration for improved predictions. We focused on arid and semiarid areas in southwestern North America since these are water-limited and experience extreme events (flooding, drought) and a wet summer monsoon season from July to September.

Our project combined three approaches for characterizing and predicting local to regional scale impacts of seasonal changes in land surface conditions. The first approach was through the establishment of a dense environmental sensor network at two small watersheds in the major deserts - a Sonoran Desert savanna and a Chihuahuan Desert shrubland. Each sensor network was designed to accomplish various objectives: 1) measure land-atmosphere fluxes at an eddy covariance site and its surrounding footprint, 2) characterize the spatial distribution of soil temperature and moisture in the watershed, 3) measure the channel runoff response at internal locations and the outlet and 4) estimate soil moisture at various levels of aggregation from point scales to the larger footprint. For each case, we selected sites in experimental rangelands where there have been prior observations and where a transition in vegetation has been documented, typically from desert grasslands to woody plant cover (shrubs or trees). The experimental watershed have been monitored continuously at a high spatiotemporal resolution for several years (5 years at the Chihuahuan desert scrubland and 4 years at the Sonoran desert savanna).

The second approach was through the use of remote sensing observations from piloted and unmanned aerial vehicle (UAV) platforms. At each site, orthophotographs and/or Light Detection and Ranging (LiDAR) were obtained from manned aircraft or UAVs and served to provide information on the site topography, vegetation cover and species distribution, and derived products such as stream hydrography. Fig. 1 illustrates an example from the Jornada Experimental Range, where the small watershed boundary was derived from a digital elevation model obtained through processing UAV-based imagery. Also depicted are the locations and

characteristics of the environmental sensor network instruments. The local scale observations from aircraft or UAVs were complemented with remote sensing from satellite platforms that provide regional estimates of surface conditions such as vegetation greenness, land temperature and surface albedo that are useful for modeling purposes.

The third approach was through the use of a high performance computing (HPC)-based hydrologic model, the TIN-based Real-time Integrated Basin Simulator (tRIBS). This physically-based, distributed model utilizes triangulated irregular networks (TINs) to describe a watershed domain and can be applied to remote areas in arid and semiarid regions for providing hydrologic predictions. To gain confidence in the model, we tested the predictions with the dense observations obtained from the environmental sensor network. Fig. 2 illustrates the type of datasets that are useful for hydrological model testing from the Santa Rita Experimental Range. Model simulations have been conducted at two small watersheds, where the simulated soil moisture and latent heat flux matched well with the site data. The model results were used to illustrate differences in runoff response due to woody-plant encroachment. Additional model testing occurred at the Jornada Experimental Range. Watershed-scale simulations that are underway utilize the individual soil profile and channel sampling locations, as well as the basin-averaged observations, for model testing purposes. In additions, innovations in using the high-performance model have been made for larger domains where the seasonal variability in land surface conditions was taken fully into account. Fig. 3 illustrates comparison of simulated land surface fields from the physically-based model in a large watershed (~3500 km^2) as compared to remotely-sensed (independent) observations of these conditions.

Our efforts in the project resulted in the following peer-reviewed publications to major international journals. These publications involved the MS students (Ryan Templeton, Nicole Pierini, Cody Anderson) and PhD students (Adam Schreiner-McGraw, Luis Mendez-Barroso, Nicole Pierini) who were trained through the project, along with collaborators identified as the projects evolved. Two additional publications are currently in review as well, as noted below, for a total of 11 peer-reviewed products from the overall effort, to date.

Vivoni, E.R., Rodriguez, J.C. and Watts, C.J. 2010. On the Spatiotemporal Variability of Soil Moisture and Evapotranspiration in a Mountainous Basin within the North American Monsoon Region. Water Resources Research. 46: W02509, doi:10.1029/2009WR008240.

Vivoni, E.R. 2012. Diagnosing Seasonal Vegetation Impacts on Evapotranspiration and its Partitioning at the Catchment Scale during SMEX04-NAME. Journal of Hydrometeorology. 13: 1631-1638.

Vivoni, E.R. 2012. Spatial Patterns, Processes and Predictions in Ecohydrology: Integrating Technologies to Meet the Challenge. Ecohydrology. 5(3): 235–241.

Vivoni, E.R., Rango, A., Anderson, C.A., Pierini, N.A., Schreiner-McGraw, A., Saripalli, S., and Laliberte, A.S. 2014. Ecohydrology with Unmanned Aerial Vehicles. Ecosphere. 5(10): art130. http://dx.doi.org/10.1890/ES14-00217.1.

Templeton, R.C., Vivoni, E.R., Méndez-Barroso, L.A., Pierini, N.A., Anderson, C.A., Rango, A., Laliberte, A.S., and Scott, R.L. 2014. High-Resolution Characterization of a Semiarid Watershed: Implications on Evapotranspiration Estimates. Journal of Hydrology. 509: 306-319.

Pierini, N.A., Vivoni, E.R., Robles-Morua, A., Scott, R.L., and Nearing, M.A. 2014. Using Observations and a Distributed Hydrologic Model to Explore Runoff Threshold Processes Linked with Mesquite Encroachment in the Sonoran Desert. Water Resources Research. 50(10): 8191–8215.

Mendez-Barroso, L.A., Vivoni, E.R., Robles-Morua, A., Mascaro, G., Yepez, E.A., Rodriguez, J.C., Watts, C.J., Garatuza-Payan, J., and Saiz-Hernandez, J. 2014. A Modeling Approach Reveals Differences in Evapotranspiration and Its Partitioning in Two Semiarid Ecosystems in Northwest Mexico. Water Resources Research. 50(4): 3229–3252.

Mascaro, G., Vivoni, E.R., and Mendez-Barroso, L.A. 2015. Hyperresolution Hydrologic Modeling in a Regional Watershed and its Interpretation using Empirical Orthogonal Functions. Advances in Water Resources. 83: 190-206.

Browning, D.M., Rango, A., Karl, J.W., Laney, C.M., Vivoni, E.R., and Tweedie, C.E. 2015. Emerging Technological and Cultural Shifts Advancing Dryland Research and Management. Frontiers in Ecology and the Environment. 13(1): 52-60.

Schreiner-McGraw, A.P., Vivoni, E.R., Mascaro, G., and Franz, T.E. 2015. Closing the Water Balance with Cosmic-ray Soil Moisture Measurements and Assessing Their Spatial Variability within Two Semiarid Watersheds. Hydrology and Earth System Sciences. (In Review).

Anderson, C.A., and Vivoni, E.R. 2015. Land Surface States within the Flux Footprint Impact Land-Atmosphere Coupling in Two Semiarid Ecosystems of the Southwestern U.S. Water Resources Research. (In Review).

Our efforts in the last reporting period (August 2014 - May 2015) focused on:

1) Continued data collection from the environmental sensor network at the Jornada Experimental Range (Fig. 1) and at the Santa Rita Experimental Range. Processing and analysis of LiDAR and UAV imagery and of the environmental sensor network data for the use in distributed hydrologic models.

2) We summarized our analysis of the Cosmic-Ray Neutron Soil moisture (CRNS) measurements in a paper to Hydrology and Earth System Sciences (Schreiner-McGraw et al., 2015, in review). Observations from the environmental sensor networks at both sites were used to validate the CRNS method, analyze the watershed hydrologic conditions, and improve parameterization of hydrologic models. The environmental sensor network allowed us to calculate the soil moisture over the full watershed to validate the CRNS method, which is an

important step because previous validations had only used point-scale sensors that do not measure the same spatial scale as the CRNS method. We found good correspondence between the two methods (RMSE = 0.012 and 0.013 m^3/m^3 at SRER and JER, shown in Fig. 4), with deviations due to bypassing of the CRNS measurement depth during large rainfall events. This limitation, however, was used in conjunction with measurements from the eddy covariance towers to show that drier-than-average conditions at SRER promoted plant water uptake from deeper layers, while the wetter-than-average period at JER resulted in leakage towards deeper soils, as depicted in Fig. 5.

3) We continued work on partitioning evapotranspiration (ET) into its components: bare soil evaporation (E) and plant transpiration (T). This work focuses on the Jornada Experimental Range (JER), and was presented at the Ecological Society of America 100th annual meeting (Schreiner-McGraw et al., 2015). We have successfully applied a method to partition ET through the use of surface soil temperature measurements and the results are promising (Fig. 6). We find that the T/ET value during the pre-monsoon season is approximately 0.3 due to plant inactivity. When the monsoon starts and plants green up, the T/ET ratio shifts dramatically and roughly 70% of ET comes from transpiration. These results are consistent with other studies in the region showing that a simple method for partitioning ET is promising.

4) We expanded the environmental sensor network at the Santa Rita Experimental Range (Fig. 7) with the installation of 24 soil sensors (8 locations with sensors at 3 depths), 4 rain gauges and 1 internal flume in watershed 7 to complement the existing environmental sensor network that was established in watershed 8 in May 2011. The new measurements help quantify the similarities and/or differences observed in soil moisture, soil temperature, rainfall, and internal runoff in the paired watersheds, which represent the landscape transition from desert grasslands (watershed 7) to woody savannas (watershed 8). The measurements in both watersheds are used in distributed hydrologic models that represent different woody plant encroachment densities depending on land management decisions.

5) We compared measurements from two eddy covariance towers at the Santa Rita Experimental Range separated by about 1.5 km in distance and 50 m in elevation. Through the processing and analysis of the flux measurements over woody savanna landscapes, we seek to discern similarities and differences due to land cover variations. As an example, Fig. 8 illustrates the daily surface energy fluxes at both locations over a 4 year study period.

These research activities have demonstrated a novel approach for terrestrial science studies by integrating the deployment of environmental sensor networks, UAV flights and HPC distributed hydrologic modeling in a range of sites in southwestern North America. Potential benefits from this research include the ability to deploy such sensor and modeling packages in battlefield environments for improved forecast of on-the-ground conditions, and for the environmental stewardship of military lands in arid and semiarid climates.

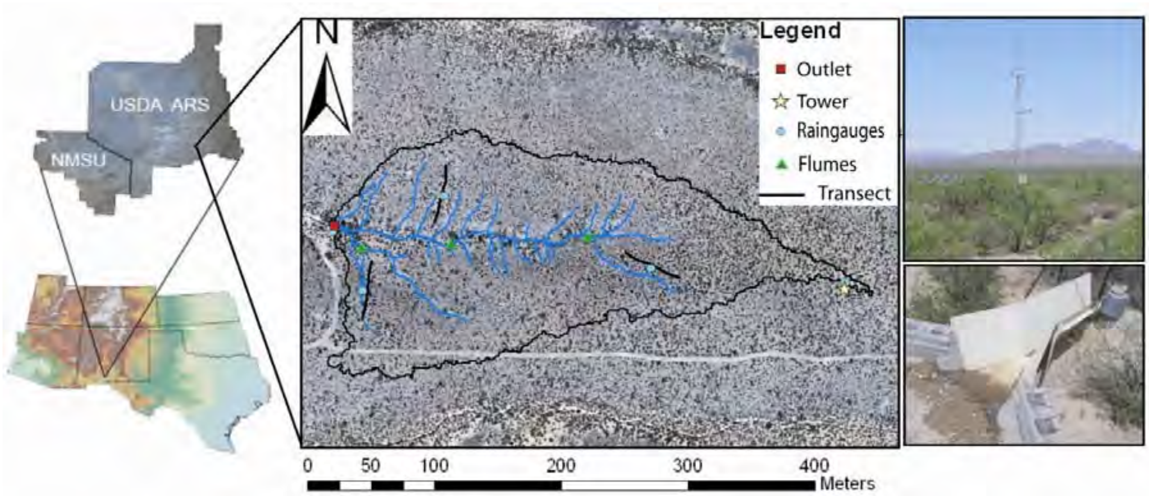

Fig. 1. Chihuahuan Desert study site at the Jornada Experimental Range, New Mexico, with watershed boundary and stream network derived from the 1-m UAV-based digital elevation model. The location of the environmental sensor network sites are shown along with two photographs depicting the eddy covariance tower and one of the channel flumes.

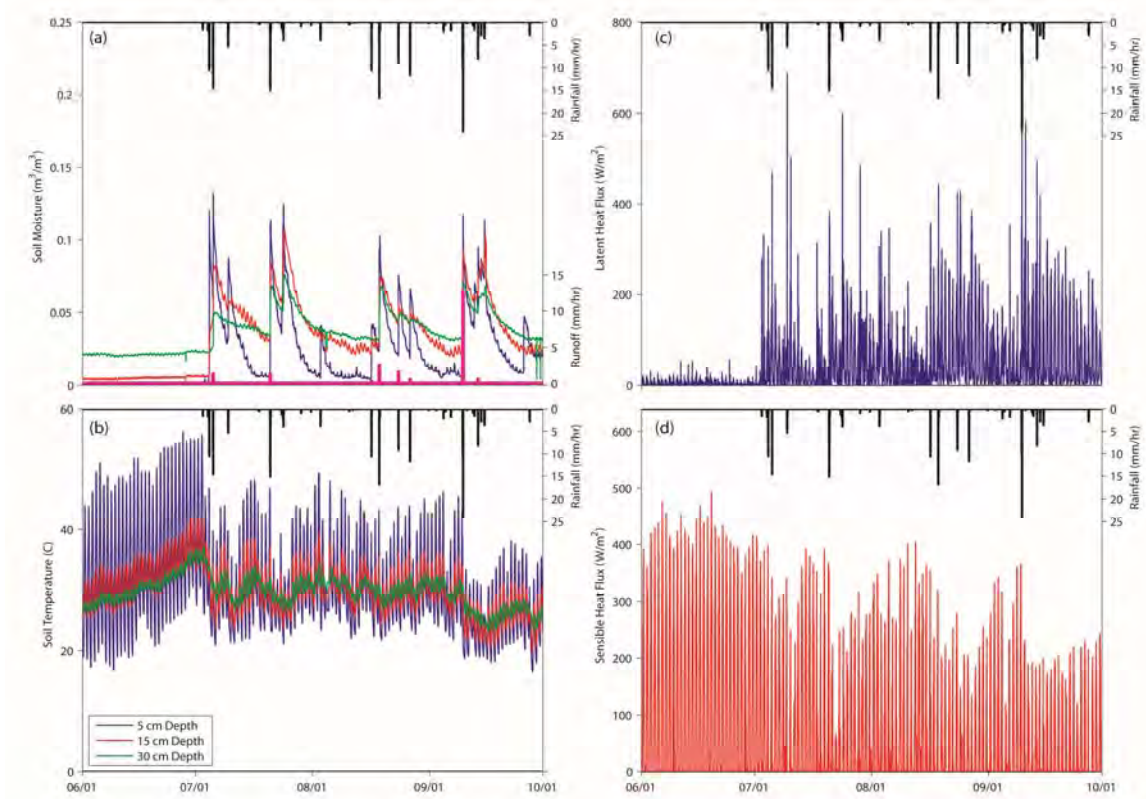

Fig. 2. Example of time series of environmental sensor network observations at the Santa Rita Experimental Range site from June 2011 to October 2011. (a) Basin-averaged rainfall rate from 5 rain gauges, runoff rate from outlet flume and basin-averaged soil moisture at 5 cm, 15 cm and 30 cm depth from 20 profile locations. (b) Basin-averaged soil temperature at 5 cm, 15 cm and 30 cm depth from 20 profile locations. (c) Latent and (d) sensible heat flux measured at the eddy covariance tower.

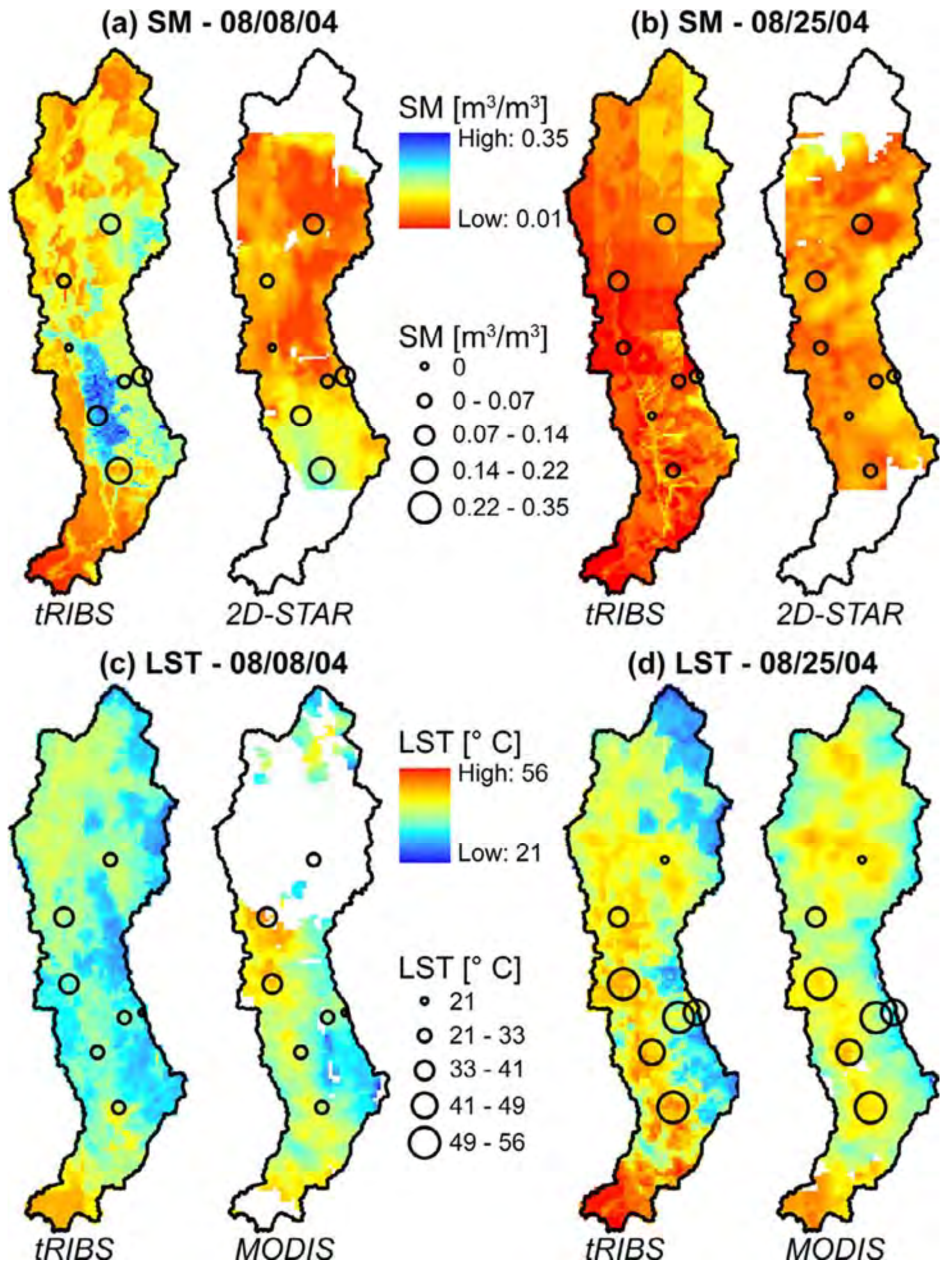

Fig. 3. High-resolution hydrologic modeling in large watersheds using high-performance computing. (a,b) Comparison of spatial patterns of simulated and retrieved (2D-STAR) surface (top 5cm) Soil Moisture (SM) on 8 and 25 August 2004.(c,d) Comparison of spatial patterns of simulated and estimated (MODIS) LST on the same days. Model outputs are for the overpass times and are resampled at same resolution (800 m for 2D-STAR and 1000 m for MODIS). White areas represent missing data. Circles of different size depict the surface SM and LST measured by individual stations at coincident times.

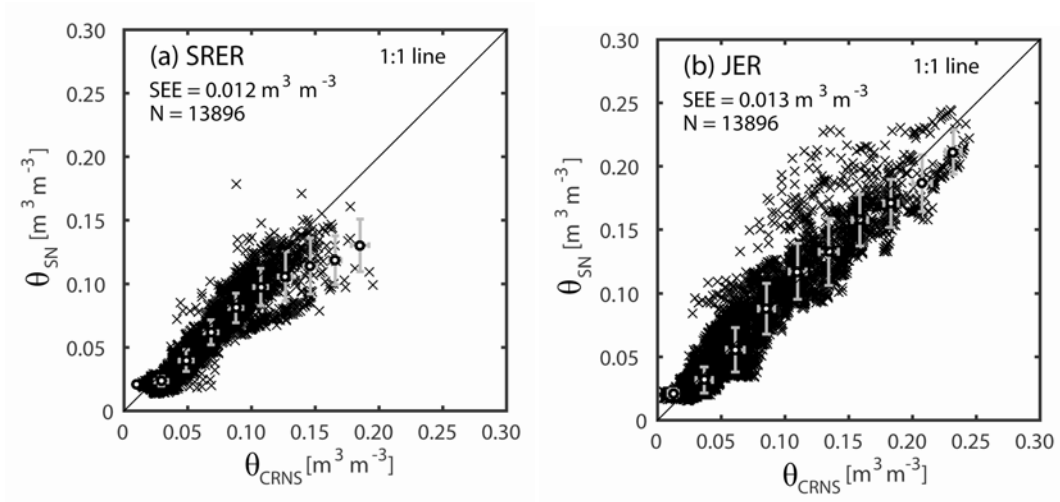

Fig. 4. Scatterplots of the spatially-averaged change in soil moisture (m^3/m^3) derived from CRNS method ($\Delta\theta_{CRS}$) and the environmental sensor network ($\Delta\theta_{SN}$) at (a) SRER and (b) JER. The SEE and the number of event samples (N) are shown for each site.

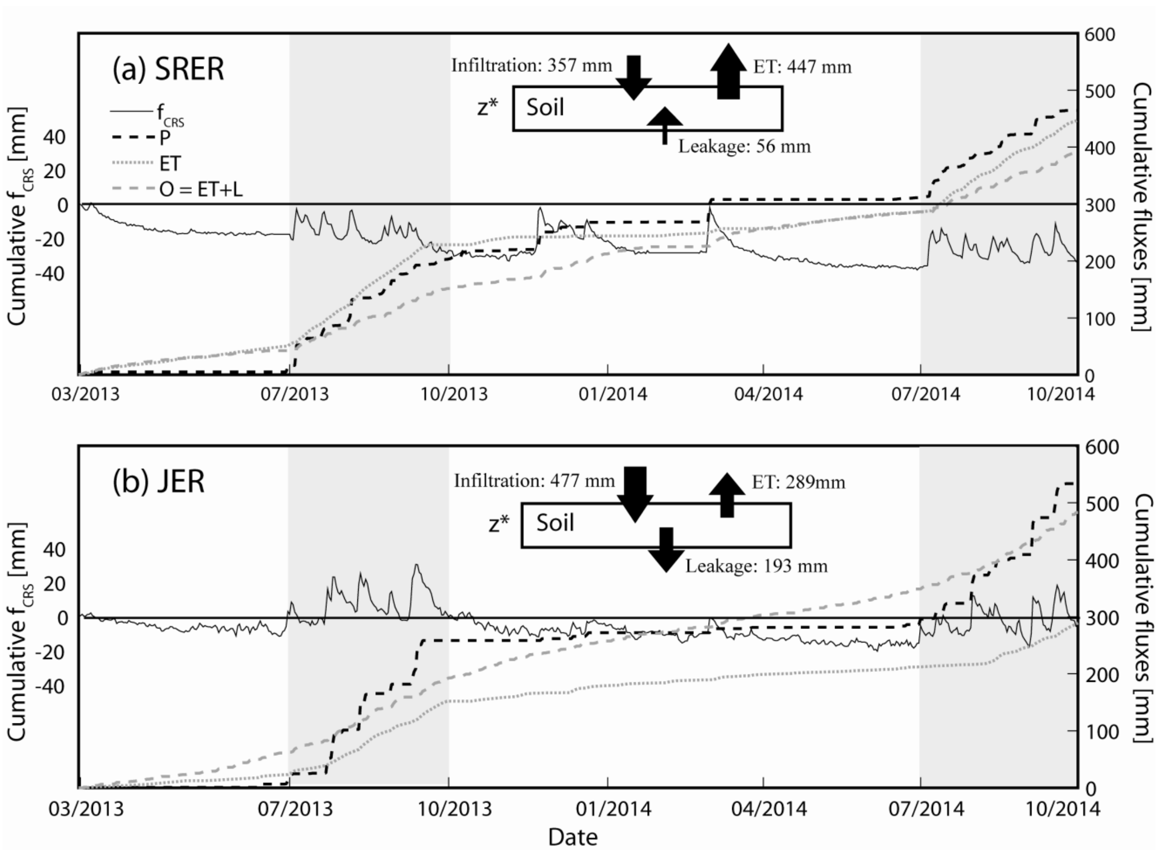

Fig. 5. Comparison of cumulative f_{CRNS} and measured water balance fluxes (P and ET). CRNS estimates of infiltration (I), outflow (O) and leakage (L) are either depicted as cumulative fluxes (O = ET + L) or as total amounts during the study period (I and L) as arrows in the soil water balance box of depth z*. Shaded regions indicate the summer seasons (July-September). The horizontal line represents $f_{CRNS} = 0$.

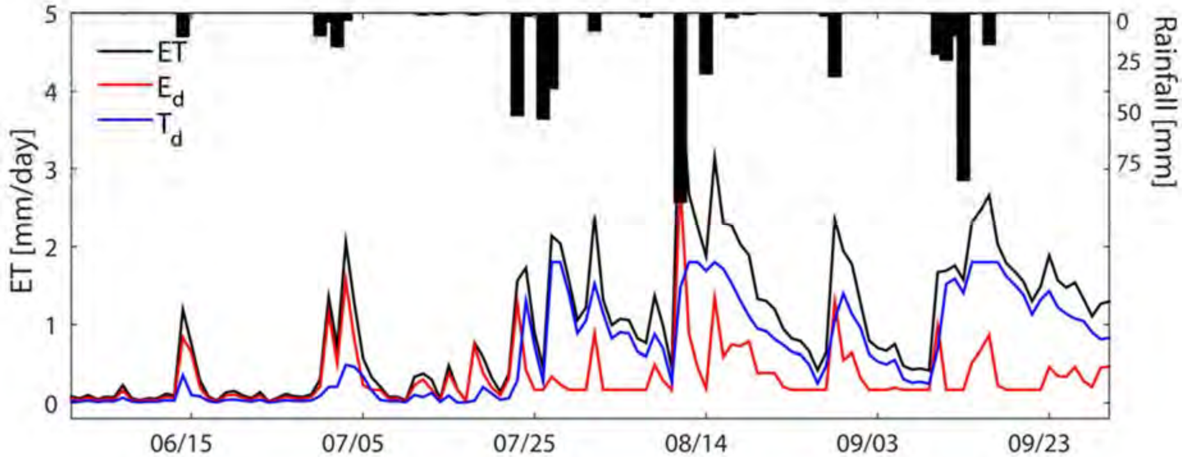

Fig. 6. Evapotranspiration partitioning at the JER for the summer of 2013.

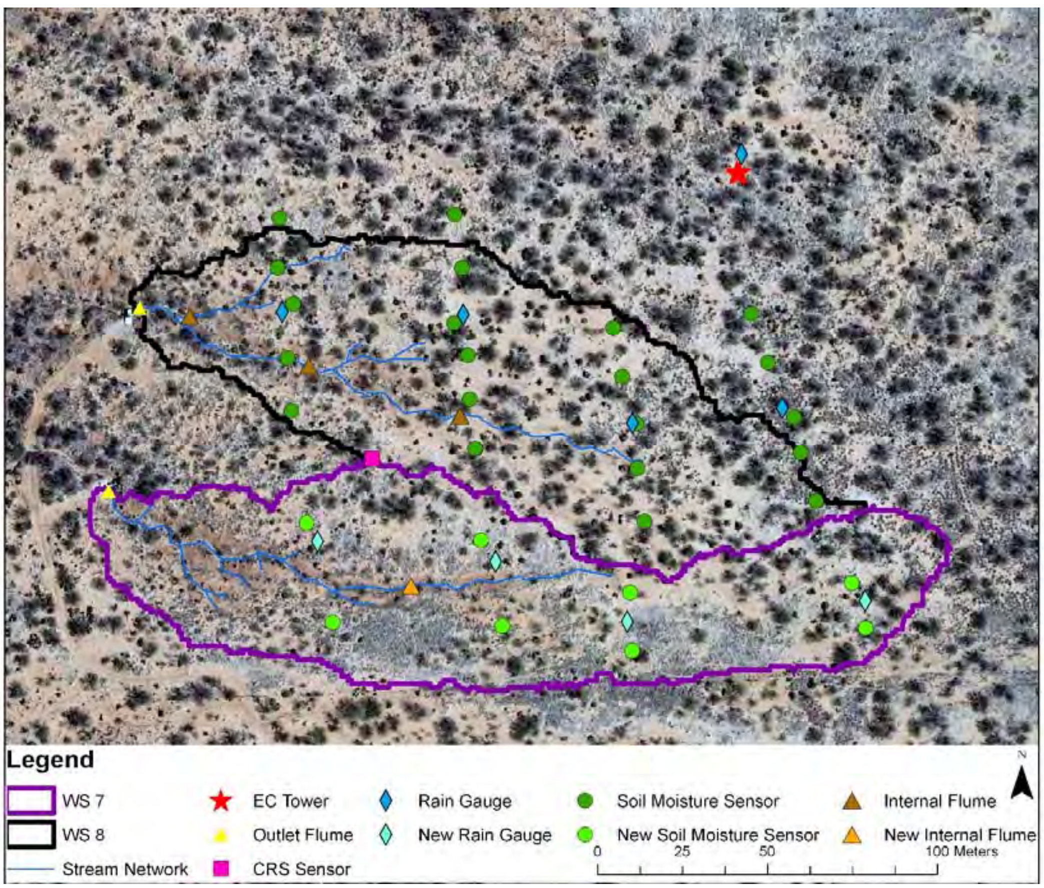

Fig. 7. Location of the study watersheds 7 and 8 (WS 7 and WS 8) within the Santa Rita Experimental Range (SRER). The 0.31 meter aerial photographs are products of the LiDAR flight taken in April 2011. The environmental sensor network was expanded into WS 7 with the addition of 24 soil sensors (at 3 depths at 8 locations) to measure soil moisture and temperature, 4 rain gauges to measure precipitation, and 1 internal mini-flume to measure runoff.

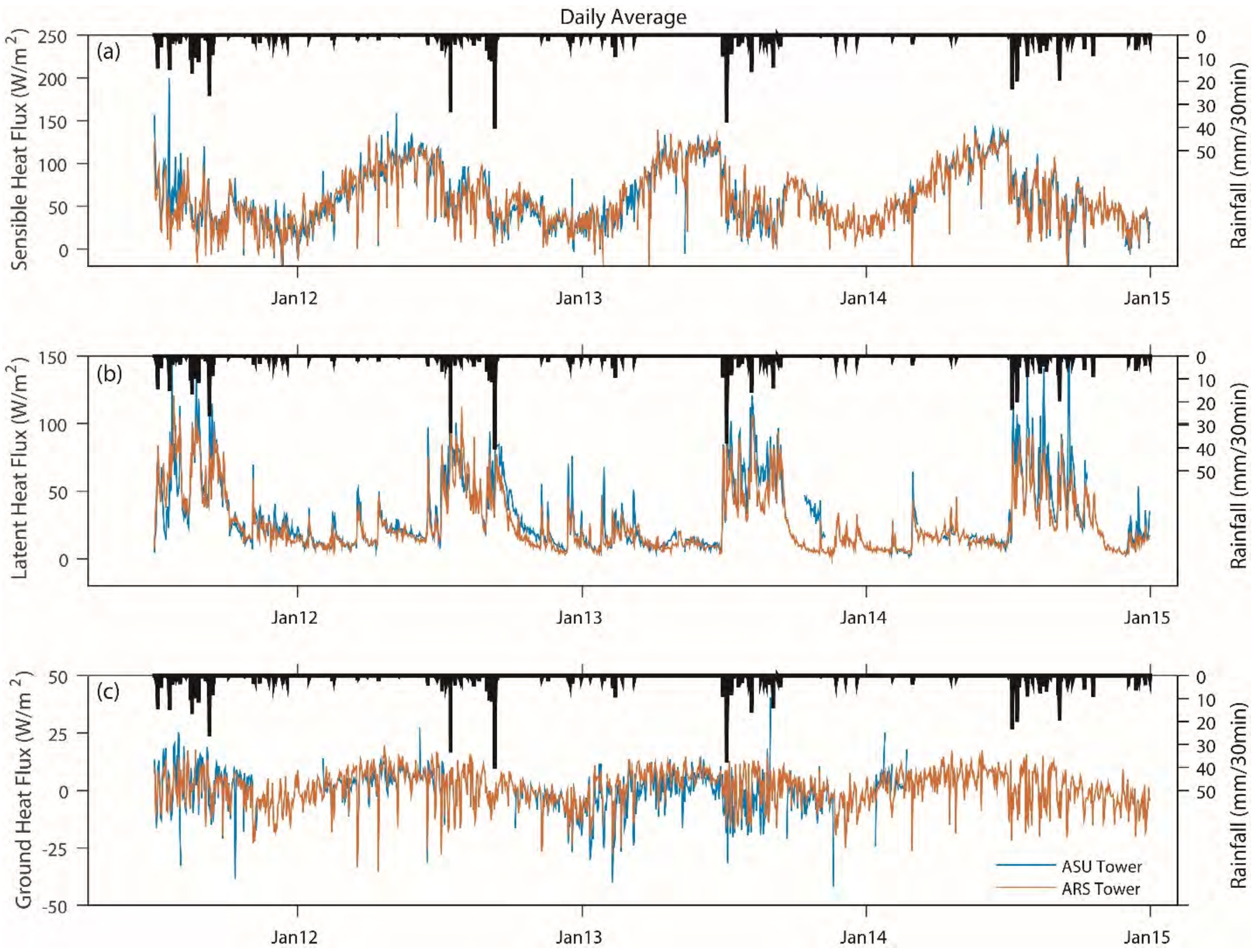

Fig. 8. Processed fluxes measured at the two eddy covariance towers (ASU and collaborating USDA-ARS measurements), including (a) sensible heat flux, (b) latent heat flux, and (c) ground heat flux, at a daily averaged time scale.